GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: 14 September 1972

Project Title: Instructional Scientific Equipment

Project No: E-21-505

Principal Investigator Dr. J. A. Connelly

Sponsor: National Science Foundation

Agreement Period: From July 1, 1972 Until June 30, 1974

Type Agreement: Grant No. GY-10344

Amount: $13,800 NSF Funds (E-21-505)
13,855 Ga. Tech Matching Funds (E-21-212)
$27,655 Total Budget

Reports Required: Final Report

Sponsor Contact Person (s): Dr. James W. Mayo, Head
Instructional Scientific Equipment Program
Division of Undergraduate Education in Science
National Science Foundation
Washington, D. C. 20550

Assigned to: Electrical Engineering

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RA-3 (6-71)

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[illegible]

GEORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF RESEARCH ADMINISTRATION

Sponsored Instruction ~~RESEARCH~~ PROJECT TERMINATION

Date: August 27, 1974*

Project Title Instructional Scientific Equipment

Project No: E-21-505

Principal Investigator: Dr. J. A. Connelly

Sponsor: National Science Foundation

Effective Termination Date: 6/30/74 (Grant Expiration)

Clearance of Accounting Charges: by 6/30/74

Grant/~~Contract~~Closeout Actions Remaining: Final Fiscal Report (NSF Form 363) by Office of Financial Affairs.

*Final Report completed 8/24/74.

Assigned to School of Electrical Engineering

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RA-4 (5/70)

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
ELECTRICAL ENGINEERING

August 21, 1974

Dr. James W. Mayo, Head
Instruction Improvement Section
Instructional Scientific Equipment Program
Division of Undergraduate Education in Science
National Science Foundation
Washington, D. C. 20550

Dear Dr. Mayo:

I am enclosing the Project Director's Final Report on NSF Grant GY-10344 (proposal No. 2/Y 50-4973) for Integrated Circuits/Systems Laboratory. This program has been in full operation since April, 1974 with the exception of one addition made to the original equipment list and purchased after all items on the original list were received. This item was a Tektronix dual trace storage oscilloscope (Model 5103N/D15) with accompaning plug-ins as detailed in the table of substitutions and additions.

Support of NSF in the development of this laboratory is sincerely appreciated. The laboratory program was written up and recently submitted to the IEEE Transactions on Education. A copy of this paper is enclosed.

Student response to the new laboratory has been quite good. To date, approximately fifteen sections of ten students each have participated. The contrast between the old electronics program which focused on discrete devices and the new one emphasizing integrated circuits and systems is particularly striking to the graduate teaching assistants. These graduate students took the old lab two years ago and now help teach the new lab. The level of interest in both undergraduate students and graduate teaching assistants has increased greatly. Interest generated by this lab has been responsible for the creation of two elective courses in electronics. These new courses, entitled Design and Applications of Operational Amplifiers and Low-Noise Electronic Design, both have associated laboratories where students individually implement their designs using state-of-the-art integrated circuits and systems. Also, the op amp course shares in the use of the equipment provided by the grant.

Other Georgia Tech faculty in Electrical Engineering have responded to the laboratory by preparing proposals of their own. Two of these have been funded by NSF during the time this grant has been active. These labs are an optical communications laboratory by Dr. William Rhodes and an acoustics laboratory by Dr. Marshall Leach.

One factor which aided considerably in securing parts for this laboratory was the donation of a number of integrated circuits, resistors, and capacitors by Harris Semiconductor and Corning Electronics. Since Atlanta does not have a good, local electronic parts supplier, most materials had to be ordered from distant suppliers with consequent delays. The assistance given by Harris and Corning alleviated somewhat this ever present problem associated with the construction of the electronic system program boards. Their interest in the project through the donation of small parts is recognized and sincerely appreciated.

Another factor which promises to aid students taking this laboratory has developed through obtaining a Model 585 Tektronix oscilloscope and three Lambda power supplies. This equipment, secured through the transfer of Federal excess property, will enable interested students to probe advanced topics suggested for independent investigation in the formal laboratory program.

This project was assisted greatly through funding of the construction costs associated with the printed circuit boards. The boards were manufactured locally to our specifications and gave a truly professional appearance to this important test fixture.

On behalf of Georgia Tech, we sincerely appreciate the support of NSF for this project and hope that funds will be available for the continuance of the Instructional Scientific Equipment Program in the foreseeable future.

Sincerely yours,

J. A. Connelly
Associate Professor of
Electrical Engineering

JAC/lc

Enclosure

INSTRUCTIONAL SCIENTIFIC EQUIPMENT PROGRAM

SUMMARY REPORT FORM

Proposal number 2/Y 50-4973

Grant number GY-10344

Date: August 19, 1974

Discipline Engineering Electrical
Broad - Detailed

TO: Division of Undergraduate Education in Science
National Science Foundation

FROM: Dr. J. A. Connelly
Project Director

Georgia Institute of Technology Atlanta, Georgia 30332
Institution

Equipment Substitutions and Additions

Requested Equipment as Listed in Original Proposal		Cost and Description of Actual Purchase	
Estimated Cost	Description	Actual Cost	Description
$1000	Ten (10), Adjustable Power Supplies, Lambda LL-903-OV	$900	Five (5) Adjustable Dual Power Supplies Tektronix PS-503
$575	Five (5) Dual, Fixed-Voltage Power Supplies, Lambda LXD-3-152	$650	Five (5) Precision Power Supplies Tektronix PS-501-1
$2975	Five (5) Function Generators, Hewlett-Packard 3310A	$1625	Five (5) Function Generators, Tektronix FG-501
		$750	Five (5) Power Module to power equipment above, Tektronix TM-503

$1700	Five (5) Digital VOMs Keithley 167	$1348	Five (5) Digital VOMs Triplett 8035
		$1170	Storage Oscilloscope Mainframe Tektronix 5103N/D15
		$285	Dual-Trace Amplifier Plug-in Tektronix 5A18N
		$495	Dual-Time Base Plug-in Tektronix 5B12N
		$375	Curve Tracer Plug-in Tektronix 5CT1N
$7500	Linear IC Tester General Radio 1730	$5700	Linear IC Tester Sitek 1420
		$980	Transfer Function Analyzer for Linear IC Tester Sitek 440
		$680	Manual Programmer for Linear IC Tester Sitek 450
		$250	Program Boards for Linear IC Tester Sitek 741, 2311

AN INTEGRATED CIRCUITS/SYSTEMS LABORATORY

J. Alvin Connelly,* Member, IEEE and Ronald Q. Perritt,† Member IEEE

ABSTRACT

This paper describes an undergraduate integrated circuits and systems laboratory which has been developed during the past year within the School of Electrical Engineering at the Georgia Institute of Technology. The objective of the integrated circuits and systems laboratory is to provide the student with the opportunity to demonstrate tangibly in the laboratory the operation and interaction of devices, circuits, and systems which he has studied or will study in the classroom.

In this laboratory students perform experimentation on (a) the characteristics and applications of two basic linear ICs, the operational amplifier and analog multiplier; (b) the operation of a successive-approximation type A/D converter and of a D/A converter; and (c) the synergistic operation of a A/D converter, D/A converter, and an operational amplifier along with other devices and subsystems to achieve a total system function.

Relatively inexpensive test experiment is used which has proven quite reliable and easy to operate. Special purpose electronic system program (ESP) boards were specifically designed, constructed, and utilized to accomodate the approximately 200 students who yearly enroll in this laboratory. This paper describes the philosophy behind this electronic systems laboratory, discusses the test equipment and ESP boards utilized, and details the specific experiments performed.

I. INTRODUCTION

Modern electronic systems employ numerous types of integrated circuits (ICs) as their principal building block to achieve desired system functions. A program for studying the operation, applications, capabilities, and limitations of ICs operating individually and in a system environment should be an essential part of any solid educational program in electrical engineering. Such a program has been established in the required electrical engineering curriculum at Georgia Tech. Under a National Science Foundation Grant,‡ equipment was purchased and experiments prepared which restructed one of the electronic laboratory facilities from its previous transistor era to an integrated circuits and systems laboratory. This change from discrete operation to ICs has made it possible to illustrate the type of system operation that is presently being applied in many industrial and research applications.

Development and mass production of reasonably inexpensive ICs has, more than any other single factor, necessitated the inclusion of system theory in the undergraduate EE curriculum. The student beginning his study of electronics, when first encountering the complex device-circuit-system principles involved in the study of electronics, is frequently overwhelmed. It has been established through classroom demonstrations that the student who experimentally traces the propagation paths of signals through the various circuits of a complex system understands the operation of the individual devices, circuits, and overall system better than a student who is only exposed to a textbook and classroom treatment. The motivation and understanding afforded by a laboratory experience of this type for all students cannot be overemphasized.

Prior to the development of integrated circuits, laboratory instruction treating system concepts was, at best, extremely difficult to incorporate into a student's formal educational program. Most of the major difficulties commonly encountered wherever such laboratory instruction was attempted involved practical limitations such as wiring complexity, power requirements, and physical size. The introduction of linear integrated circuits has radically lessened each of these practical limitations to such an extent that it is now practically feasible, and quite necessary as well, to provide all students with "hands on" laboratory experience as an essential part of their formal educational program.

The objective of the integrated circuits and systems laboratory is to provide the student with the opportunity to demonstrate tangibly in the laboratory the operation and interaction of devices, circuits, and systems which he has studied or will study in the classroom. This objective is realized by utilizing linear and digital integrated circuits as basic building blocks in linear and non-linear electronic systems and studying the performance of these systems. The laboratory emphasizes the characteristics, applications, and interconnections of linear integrated circuits as electronic subsystems. Details of specific exercises are given in Section IV.

II. OPERATIONAL STRUCTURE OF THE LABORATORY

Students at Georgia Tech normally take one required EE laboratory course each quarter beginning with a basic instrumentation laboratory the last quarter of the sophomore year and culminating in a project laboratory the last quarter of the senior year. With the exception of the first and last laboratories (EE 3400 and EE 4430) all laboratories are separate from required courses, carry one hour academic credit, and meet once per week for three hours.

The Integrated Circuits/Systems Laboratory (EE 3420) is the third laboratory course all Electrical Engineering students take. Enrollment in this course averages 200 students per year with the heaviest enrollment of approximately 70 students during the winter quarter. This large enrollment imposes certain operational constraints upon the management and structure of the laboratory.

Maximum benefit would result for all students if each could work individually. This arrangement, however, is cost prohibitive. As a compromise, experimental investigations are conducted in groups of two. Five identical stations provide laboratory positions for ten students per period. During the heaviest quarter, this laboratory operates from noon to 6 p.m. four days per week and from 3 to 6 p.m. on the fifth weekday for a total of nine, three-hour periods per week. (During lighter quarters, the laboratory is shared with a senior elective course and lab on operational amplifiers.)

Due to the large enrollment in this IC laboratory, it was necessary to build some formal structure into the student experimentation. Experiments were prepared with a basic, core procedure required to be performed by all students. The nominal time required to perform this standardized procedure was two hours, leaving approximately one hour available for independent investigations. Students were encouraged to discuss original ideals relating and extending the basic procedure previously illustrated and to conduct additional, original experimentation extending the laboratory concepts.

III. LABORATORY EQUIPMENT

Selection of test instrumentation for equiping the five test stations was based upon economy, reliability, and ease of operation. Each station was provided with the basic pieces of equipment shown in Figure 1. The cost of each station was approximately $3000. Reliability of this equipment has been excellent during the first three quarters of operation during which this equipment has served approximately 200 students. These students have quickly learned to properly operate this test equipment. The oscilloscope system utilized is extremely versatile with dual-trace and four-trace plug-in amplifiers which permit simultaneous signal monitoring of up to six different circuit points in all systems investigated.

A centralized test station was established at a cost of approximately $8000 for use by all students to rapidly evaluate a wide variety of linear ICs. This central station features a Linear IC Tester as shown in Figure 2 with the capability of measuring performance parameters of op amps, voltage regulators, phase-locked loops, voltage comparators, and digital-to-analog and analog-to-digital converters. Students utilize this instrumentation to help determine whether a system limitation is due to device performance or circuit interactions.

Each station has been equiped with specially constructed test fixtures for all experimental exercises. These fixtures, known as the "Electronics System Programmer" (ESP) boards, contain the circuits composing the various systems investigated. These fixtures were designed in a printed-circuit board fashion. The larger ESP boards are supported on wooden frames for rigidty. Terminals are attached to the printed circuit boards for making external connection to power supplies and signal sources. Other necessary controls and switches are attached to the PC board. (Socket mounting was employed for all integrated circuits, transistors, and other semiconductor devices to facilitate their removal for testing with the Linear IC Testor.) Test points have been provided on the fixtures at appropriate locations for signal monitoring via the scope. Other interconnections between the various circuits on the ESP fixture are by plug wire and/or 50 Ω coaxial cable whenever possible. Inputs and outputs to these circuits were available for interconnections, and also for isolated study of a particular circuit configuration.

Figure 3 shows several of the ESP boards utilized in the laboratory. Average component cost for the ESP fixtures (including the printed-circuit board) was about $40 each. The cost of the ESP fixture for the analog-to-digital experiment was approximately $60. TTL buffers were utilized in conjunction with the A/D and D/A converters to make all inputs and outputs compatible with TTL/DTL logic levels.

IV. EXPERIMENTAL EXERCISES

As previously stated, this laboratory was developed to demonstrate the operation of devices, circuits, and subsystems to achieve a total system function. In order to achieve this objective, the following exercises were developed:

Experiment I. CHARACTERISTICS OF OPERATIONAL AMPLIFIERS

Experiment II. APPLICATIONS OF OPERATIONAL AMPLIFIERS

Experiment III. ANALOG-TO-DIGITAL AND DIGITAL-TO-ANALOG CONVERSION SYSTEMS

Experiment IV. ANALOG ARITHMETIC SYSTEMS

A brief description of each of the experiments will be given followed by a more detailed discussion of Experiment III.

Characteristics of Operational Amplifiers:

The primary objective of this experiment is to familiarize the student with the salient performance parameters of operational amplifiers, e.g., open-loop gain, bandwidth, input offset voltage and current, slew rate, etc. An ESP board was constructed for testing a 741 Op Amp using appropriate external elements and switches. With this board, a function generator and an oscilloscope, students can either measure the op amp parameters directly or calculate through simple formulae these parameters from measured data. The 741 amplifiers are then tested at the control test station using the Sitek Linear IC Tester to compare measured parameters against a reliable standard. In most cases agreement between measurements is typically 5% or less. Through this process, students quickly learn typical parameter values and the accuracy they can expect from their measurements in the laboratory.

Applications of Operational Amplifiers:

This exercise extends the concepts introduced in Experiment I by demonstrating some of the basic linear applications of Op Amps using negative feedback. Using another ESP board, students evaluate the performance of circuits with the following functions:

(a) inverting and noninverting gain stages with both dc and ac inputs (with ac inputs, frequency response and gain bandwidth considerations are emphasized).

(b) summing amplifier (combining sinusoidal and square waves are illustrated).

(c) integrator and differentiator (time response of these circuits to various inputs are investigated).

This experiment not only shows important basic applications of op amps but illustrates the relationship which exist among the parameters of an op amp and circuit performance. For example, in (a) above, the frequency response of the closed-loop gain is shown to depend on the frequency characteristics of the open-loop gain.

Students were encouraged to propose and carry out investigations on their own of other applications of op amps for both linear and nonlinear functions. Some extensions students have developed include op amp active filters, current amplifiers, and absolute value circuits.

Analog-To-Digital and Digital-To-Analog Conversion Systems:

This experiment was divided into three parts: the A/D system, the D/A system, and the combined A/D/A system: The A/D system utilized an 8-bit, successive approximation converter. A special ESP board was designed which provided both parallel and serial outputs with an LED "state indicator" for monitoring each of the parallel output bits. Using the definition of resolution, students calculated the appropriate 8-bit digital code for various input voltages once the full-scale, output voltage was specified. They then compared their theoretical results with results obtained using the A/D converter. Building upon this basic concept, exercises were performed to illustrate the following points:

(a) the timing and sequence of operations needed to make one complete analog-to-digital conversion.

(b) the convergence of the successive approximation technique.

(c) the relationship between the serial output data and the parallel output data.

Each of the above concepts, while difficult to describe orally, was easily illustrated in the lab using the ESP board and the multitrace oscilloscope.

The second part of this experiment focused on a digital-to-analog conversion system. An ESP board was designed to accept either parallel input data or serial input data. A D/A converter module was used to accomplish the D/A conversion. Using the parallel input terminals, various combinations of input data were applied and the relationships between theoretical and actual analog outputs were determined.

In the third part of this experiment, the A/D system was employed to provide the input for the D/A system so that the entire A/D/A process could be studied. The overall system was examined for both parallel and serial data transmission for various input voltage waveforms and frequencies. Students quickly recognized the need for a functional sample-and-hold circuit when converting serial data. The linearity of the overall system was determined. Relationships between the conversion frequency and input signal frequency and the effects of these relationships on the ability of the D/A system to reconstruct the original analog input were easily demonstrated.

Analog Arithmetic Systems:

The basic objective of this experiment was to demonstrate the operation of an analog, four-quadrant multiplier. A special test fixture was constructed which permitted investigation of offset and level shifting adjustments required for a MC1594 multiplier and its associated op amp buffer circuitry. Outputs were monitored for various combinations of input signal levels, waveforms, and frequencies.

By making some circuit modifications using switches on the test fixture, the multiplier system was used to accomplish other analog operations such as squaring, square root extraction, and division. Using the analog multipliers, students illustrated several basic communications principles such as AM modulation and detection.

V. FOCUS ON THE A/D/A SYSTEM

A block diagram of the A/D converter is shown in Figure 4. With a 5.10 volt reference input, the 8-bit converter provides a resolution of 20mV. The potentiometer P_1 provides a dc input voltage which is easily adjusted (with a 10-turn pot) between zero and full scale with switch S_1 in position B. At the end of each conversion cycle, the strobe signal causes the latches to hold the parallel output data while the LEDs display a visual indication of the state of each output bit.

Figure 5 shows a lab station test setup with the necessary power supplies, function generators and oscilloscope for the A/D converter. The clock signal is derived from a separate, small PC board which uses a 555 IC timer. This leaves the function generator available as an external signal source which is needed during several portions of the experiment. The internally generated strobe signal is available at two points on the ESP board. One strobe output synchronizes the scope and the other connects to the D/A ESP board. A ladder output terminal facillitates observation of the sequence of events which make up one complete conversion cycle.

The block diagram of the D/A converter system is shown in Figure 6. The input-mode switch S_2 selects input data furnished in either a parallel format or a serial format from the A/D board. The input selector then routes the data to the inputs of the D/A converter module. The input selector function is accomplished with two multiplexers (74157 ICs). When S_2 is in position A the output of the D/A converter is fed into a sample-and-hold circuit which maintains a constant output voltage level during each conversion cycle. When parallel input data are used, the clock, strobe and sample/hold circuit are not used; the output is taken at Output B.

Figure 7 shows the complete A/D/A system connected for the transmission of serial data. Note that three coaxial cables are used to carry the clock, strobe and data signals.

The overall operation of the A/D/A system can be easily illustrated by referring to Figure 8. This figure shows a sinusoidal analog input signal to the A/D system and the digitally converted output of the sample-and-hold circuit circuit on the D/A system (top trace). The lower trace shows the system output with the same input when the clock frequency is relatively lower by a factor of 3 over that used for the top trace.

The A/D/A system is extremely flexible; there are many possible exercises which could be done. One such exercise which is performed is to measure the linearity of the overall system. An exercise which should not be overlooked is system calibration. Potentiometers are provided on each test fixture for this purpose. Note that the input range on the A/D system is 0-5.10 V whereas the output range is typically 0-10 V on the D/A system. The full scale output can be adjusted to 10.20 V so that the system has a "gain" of 2.

VI. CONCLUSIONS

The integrated circuit laboratory described in this paper has served as a reliable and relatively inexpensive vehicle for allowing approximately 200 undergraduate students per year to obtain "hands-on" experience with practical electronic systems. Commercially available test equipment was selected for its versatility and ease of student operation. Special purpose electronic system program boards are described which use miniature switches to permit alteration of circuit configurations, thereby providing easy implementation of many experimental circuits without requiring an excessive number of connecting wires. The philosophies and operational considerations were discussed for student experiments involving operational amplifier applications and terminal parameter measurements; individual A/D and D/A converter operations and a complete A/D/A system; and for a four-quadrant analog multiplier.

LIST OF FIGURES

FOOTNOTES

* The authors are with the School of Electrical Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332.

† R. Q. Perritt is on leave from the Department of Electrical Engineering, Louisiana State University, Baton Rouge, Louisiana 70803.

‡ National Science Foundation Grant GY-10344 to J. A. Connelly.